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(54) **SYSTEMS AND METHODS FOR AMPLIFYING LIGHT**

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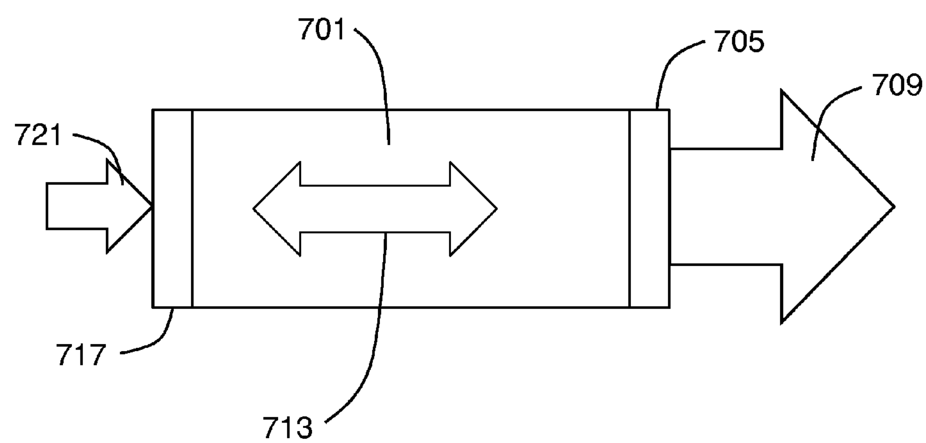
(57) **ABSTRACT**

The invention relates to optical system including light sources that amplify light using a gain medium. Systems and method of the invention are provided for amplifying light while inhibiting reflections at a peak gain of the gain medium, thereby suppressing parasitic lasing. This allows a system to use a broad range of wavelengths without parasitic lasing, thereby increasing the useable range of a tunable optical filter. In this manner, light at wavelengths not at a peak gain can be used effectively, and the gain medium of an optical amplifier does not limit use of a system to a narrow range of wavelengths associated with a peak gain of the gain medium. A single optical system according to the invention can thus be used for applications that require a broad range of wavelengths.

18 Claims, 15 Drawing Sheets



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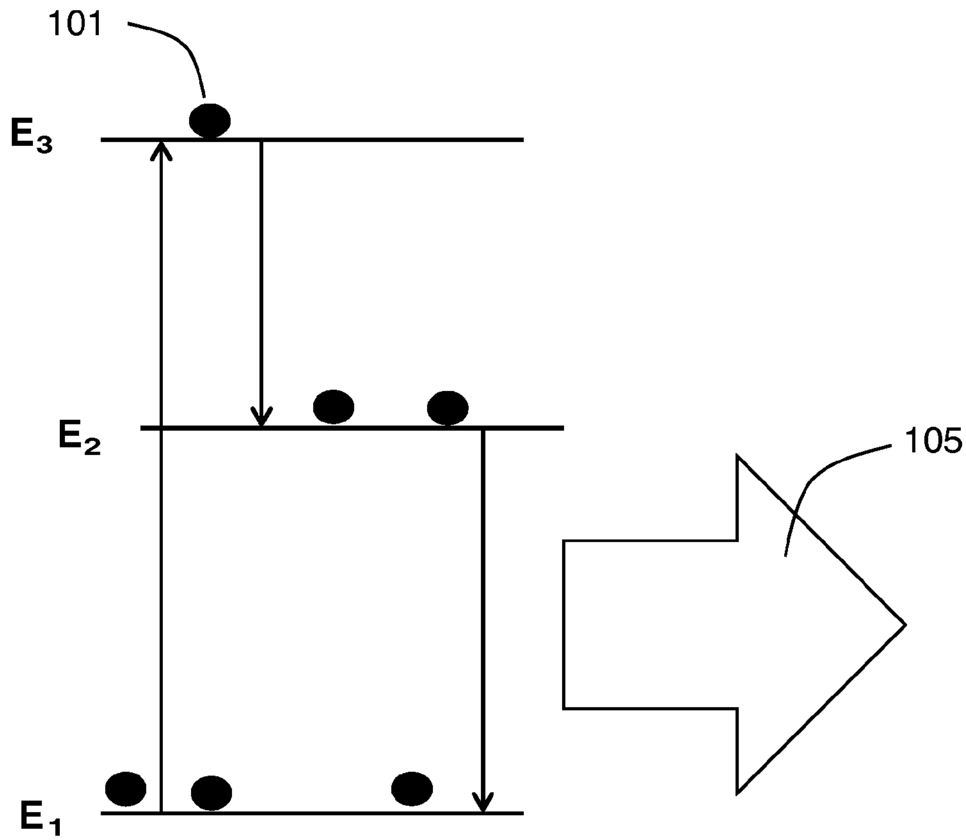

FIG.1

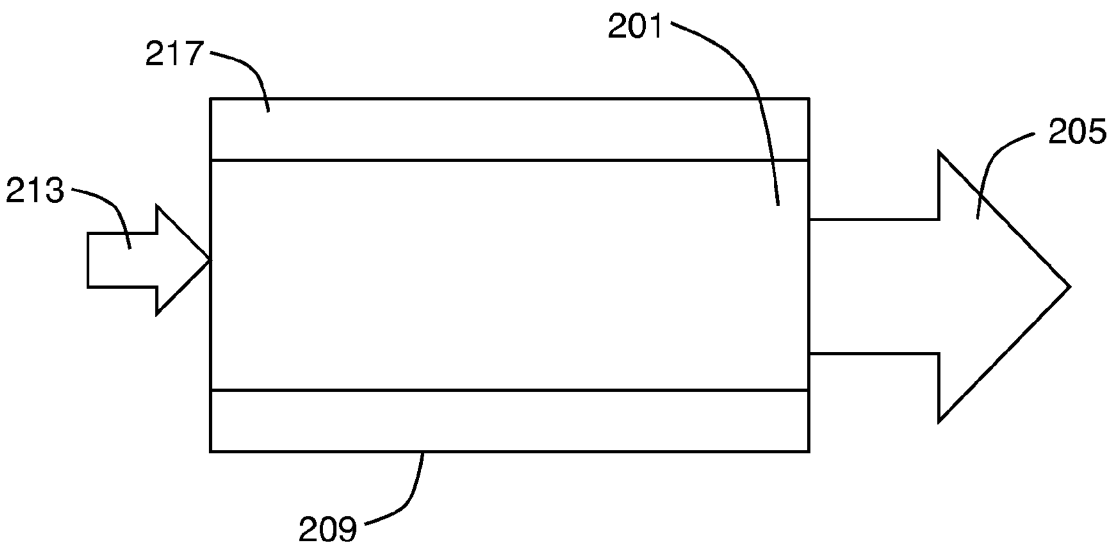

FIG.2

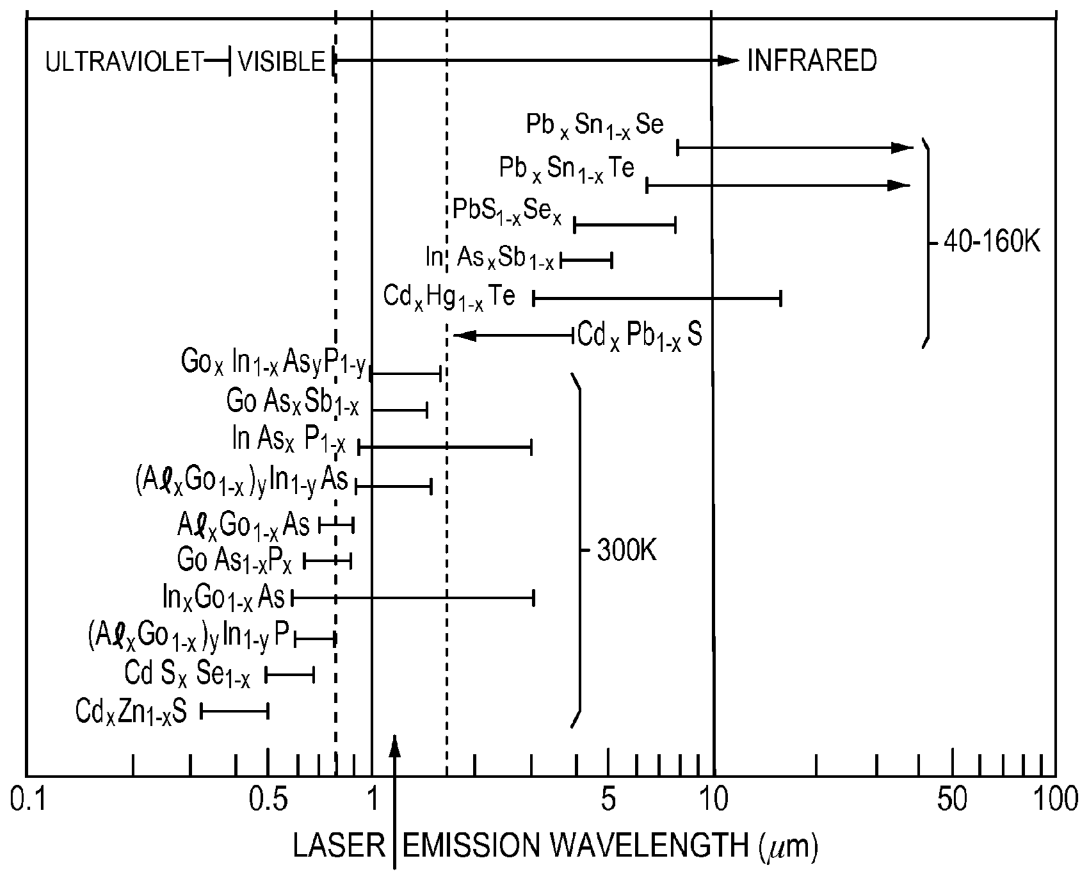
ULTRAVIOLET
VISIBLE
INFRARED
Pb x Sn 1-x Se
Pb x Sn 1-x Te
PbS1-x Sex
In AsxSb1-x
CdxHg1-x Te
Cd x Pb1-x S
40-160K
Gox In1-x AsyP1-y
Go AsxSb1-x
In Asx P1-x
(AlxGo1-x)yIn1-y As
AlxGo1-x As
Go As1-xPx
InxGo1-x As
(AlxGo1-x)y In1-y P
Cd Sx Se1-x
CdxZn1-xS
300K
0.1
0.5
1
5
10
50
100
LASER EMISSION WAVELENGTH (μm)

FIG.3

Thorlabs BOA1130S and BOA1130P

Item #		BOA1130S and BOA1130P		
		Min	Typical	Min
Operating Current	I_{OP}	-	700 mA	750 mA
Center Wavelength	λ_C	1265 nm	1285 nm	1295 nm
Optical 3 dB Bandwidth	BW	80 nm	87 nm	-
Saturation Output Power (@ -3 dB)	P_{SAT}	15 dBm	17 dBm	-
Small Signal Gain (@ Pin = -20 dBm, λ = 1312 nm)	G	27 dB	30 dB	-
Gain Ripple (RMS) @ I_{OP}	$\bar{o}G$	-	0.2 dB	0.3 dB
Noise Figure	NF	-	7.0	9.0
Forward Voltage	V_F	-	1.6 V	2.0 V
Chip Length	-	-	1.5 mm	-
Waveguide Refractive Index	-	-	3.2	-
TEC Operation (Typ./Max @ T_{CASE} = 25/70 °C)				
- TEC Current	I_{TEC}	-	0.4 A	1.5 A
- TEC Voltage	V_{TEC}	-	0.5 V	4.0 V
- Thermistor Resistance	R_{TH}	-	10 KΩ	-

FIG.4

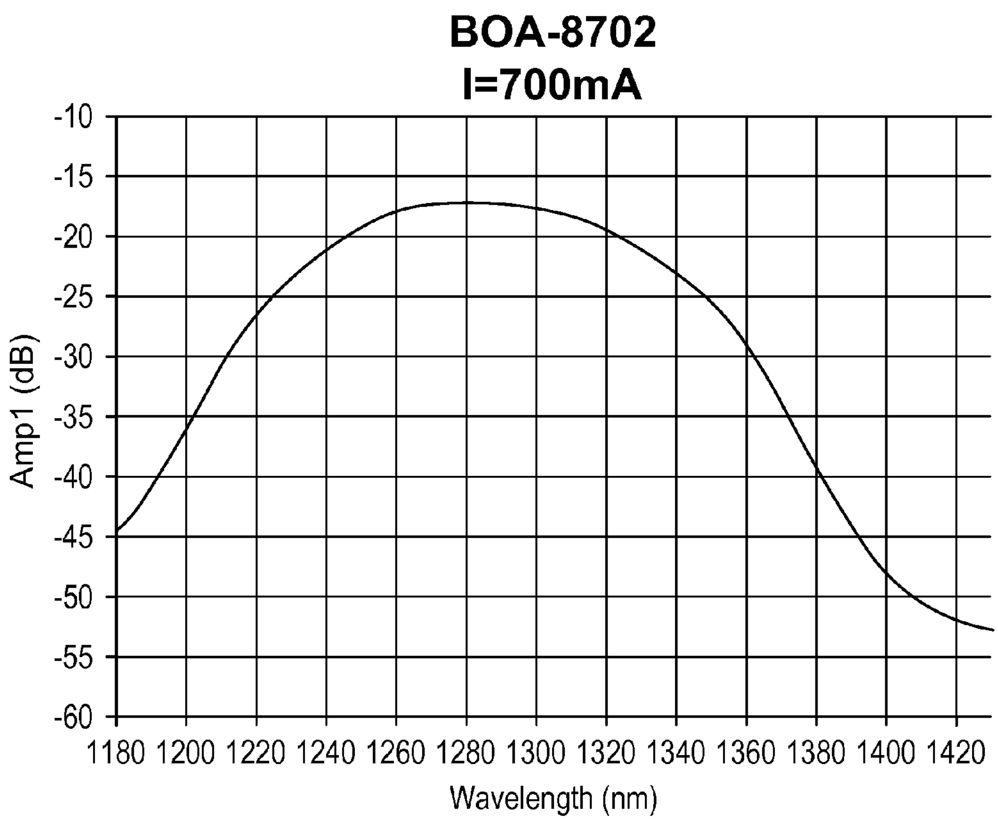
BOA-8702
I=700mA
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
Amp1 (dB)
1180 1200 1220 1240 1260 1280 1300 1320 1340 1360 1380 1400 1420
Wavelength (nm)

FIG.5

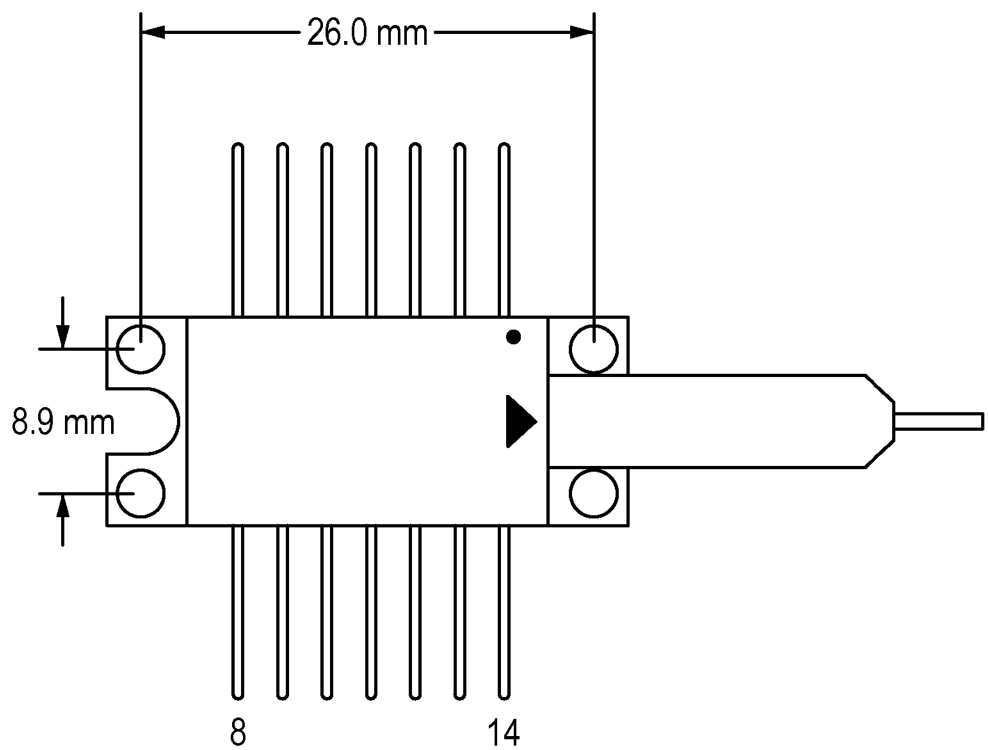

FIG.6

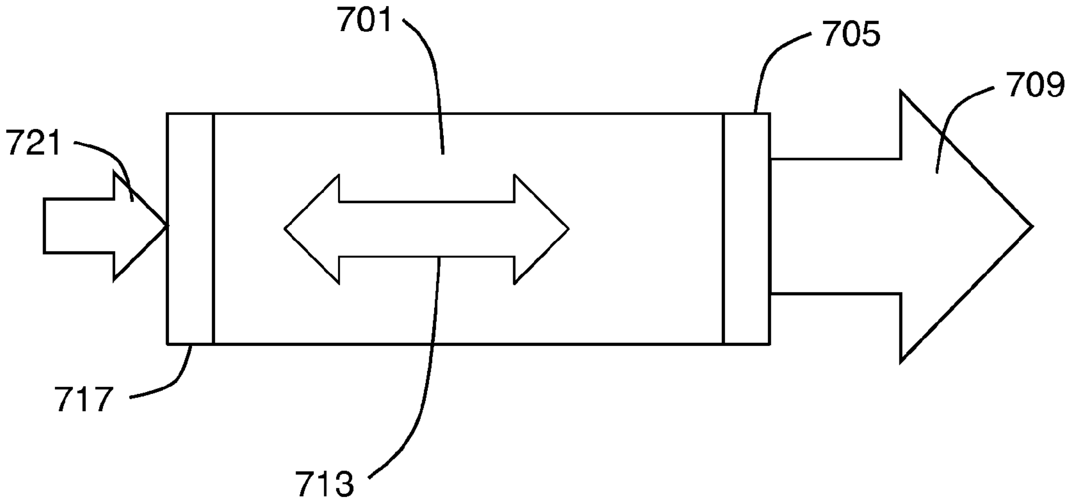

FIG.7

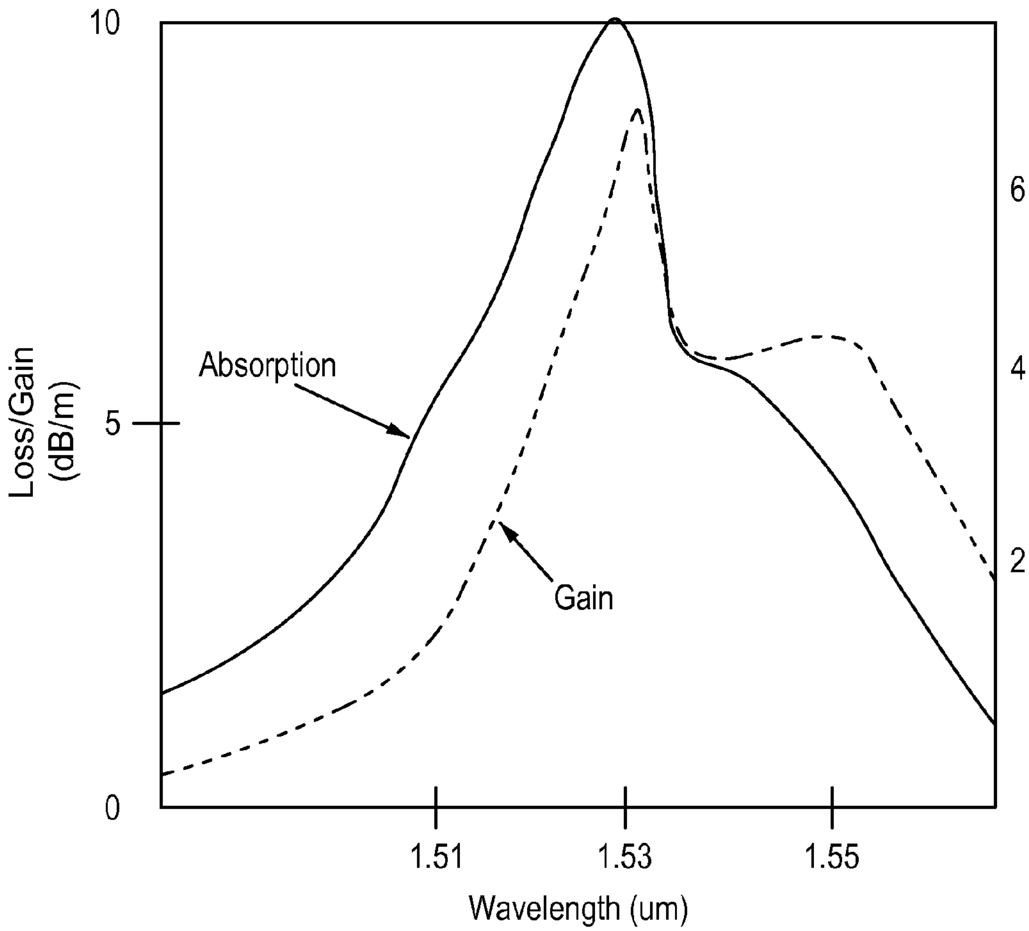
10
5
0
Loss/Gain
(dB/m)
Absorption
Gain
6
4
2
1.51
1.53
1.55
Wavelength (um)

FIG.8

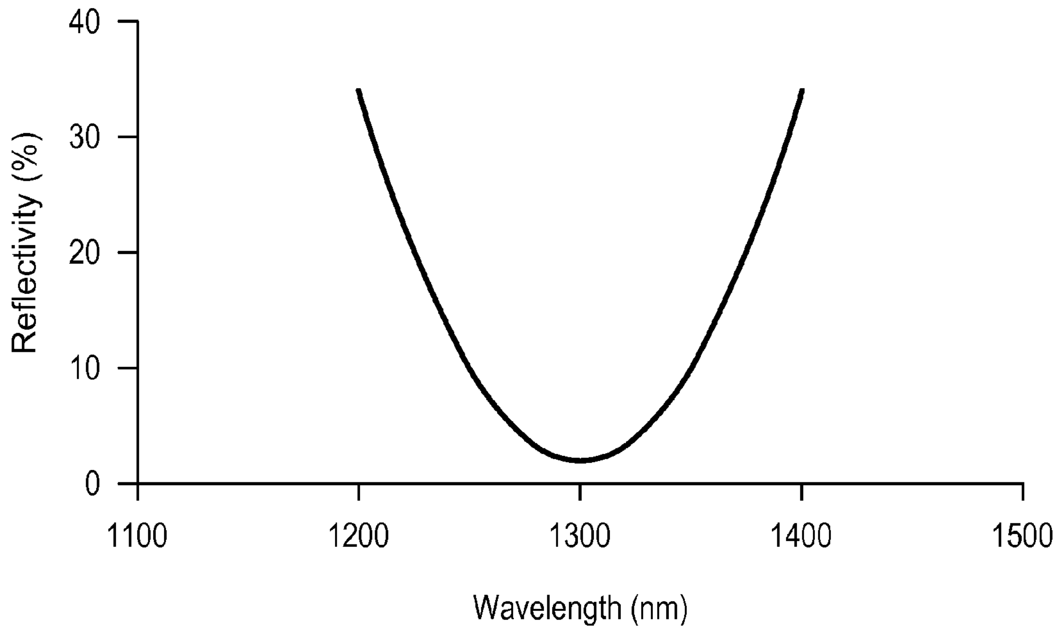
40
30
20
10
0
Reflectivity (%)
1100
1200
1300
1400
1500
Wavelength (nm)

FIG.9

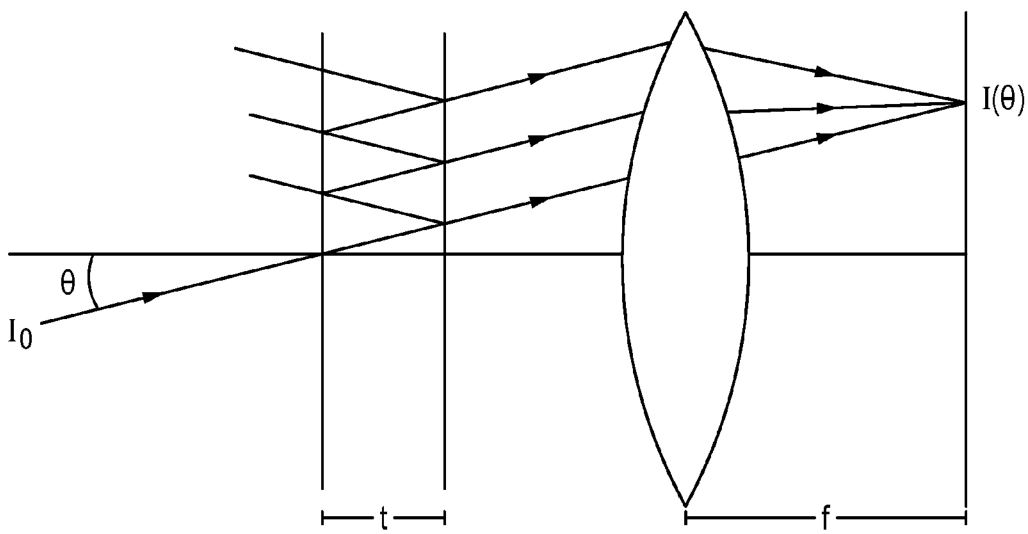

FIG.10

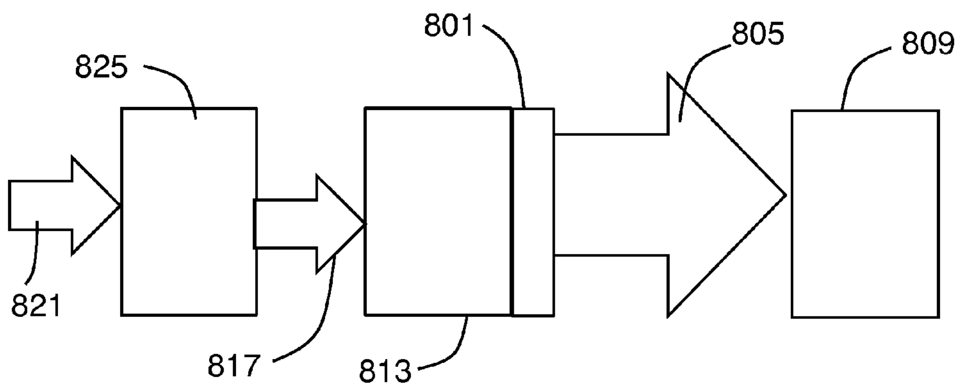

FIG.11

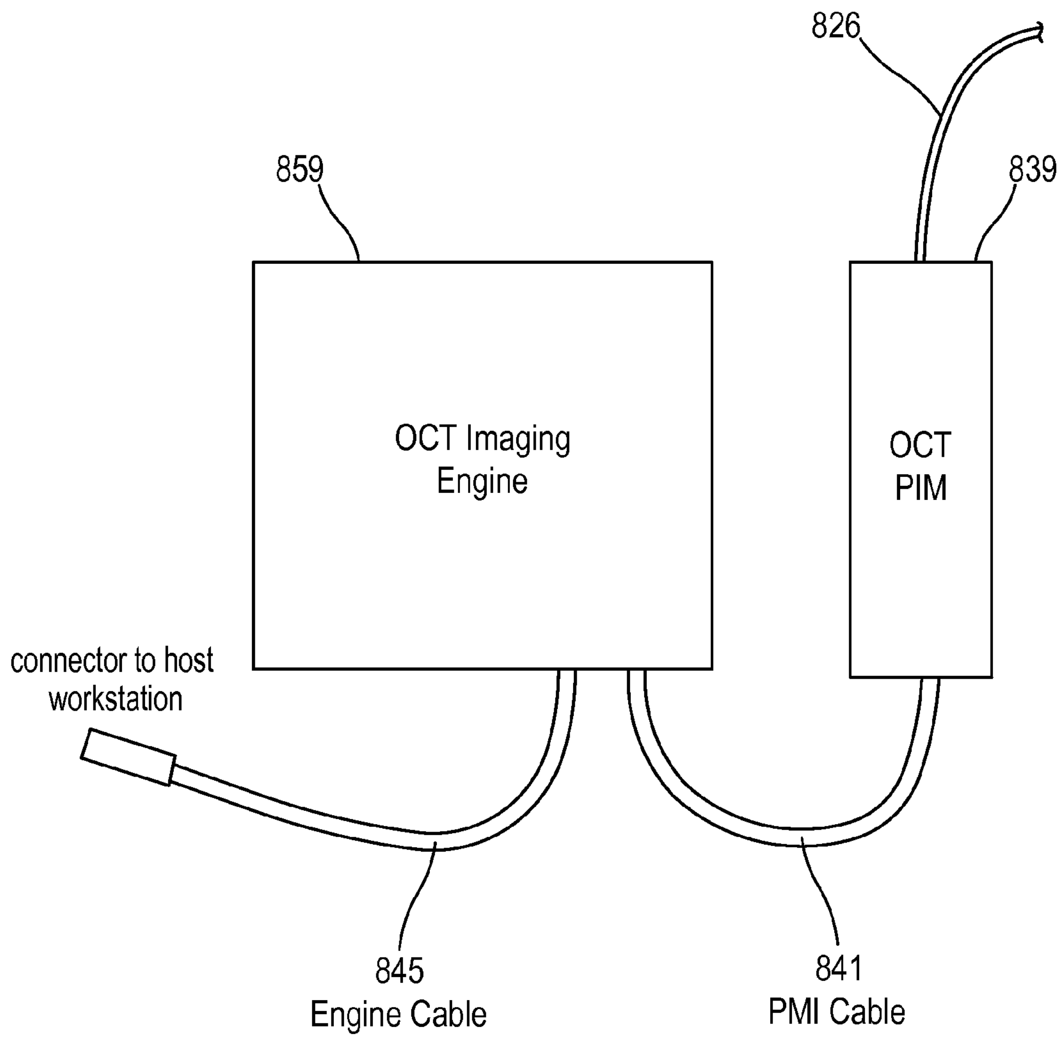
826
859
839
OCT Imaging Engine
OCT PIM
connector to host workstation
845
Engine Cable
841
PMI Cable

FIG.12

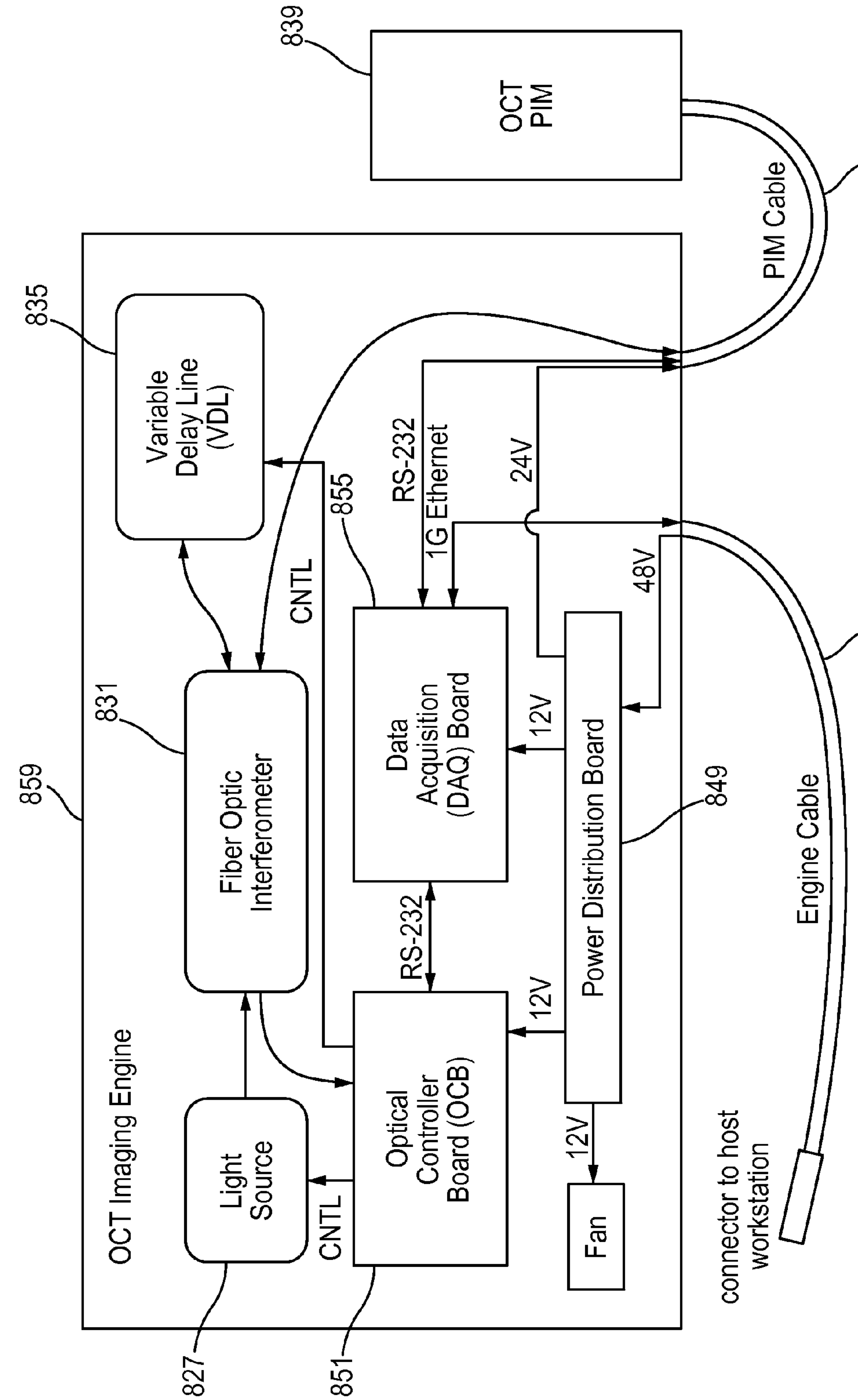
839
OCT PIM
841
PIM Cable
835
Variable Delay Line (VDL)
859
831
Fiber Optic Interferometer
CNTL
855
RS-232
1G Ethernet
24V
48V
Data Acquisition (DAQ) Board
12V
Power Distribution Board
849
845
Engine Cable
RS-232
12V
OCT Imaging Engine
Light Source
CNTL
Optical Controller Board (OCB)
12V
Fan
connector to host workstation
827
851

FIG.13

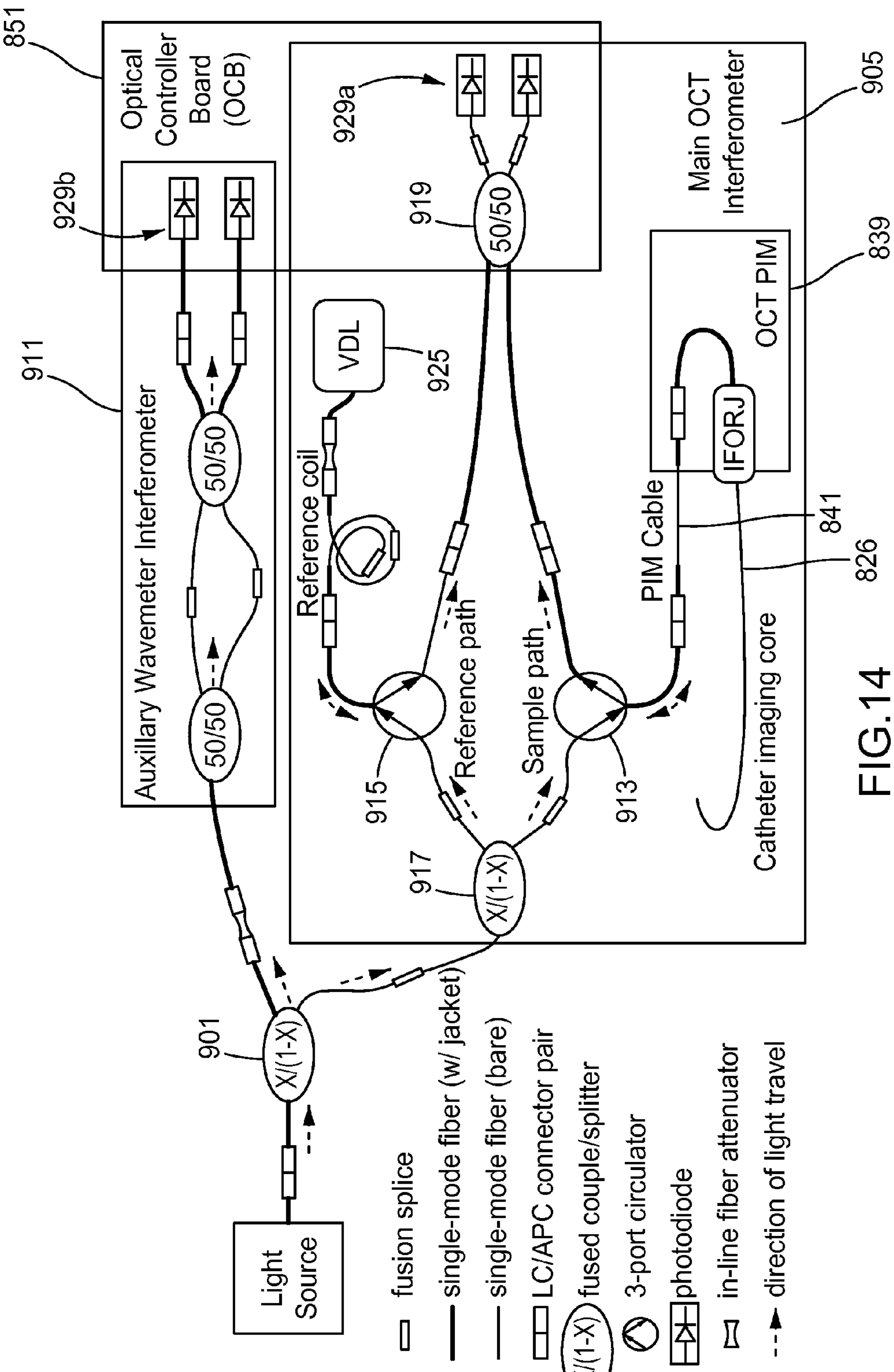
851
Optical Controller Board (OCB)
929b
929a
919
50/50
Main OCT Interferometer
905
911
Auxillary Wavemeter Interferometer
50/50
50/50
VDL
925
OCT PIM
839
IFORJ
Reference coil
PIM Cable
841
826
Reference path
Sample path
915
913
917
X/(1-X)
Catheter imaging core
901
X/(1-X)
Light Source
fusion splice
single-mode fiber (w/ jacket)
single-mode fiber (bare)
LC/APC connector pair
X/(1-X) fused couple/splitter
3-port circulator
photodiode
in-line fiber attenuator
direction of light travel

FIG.14

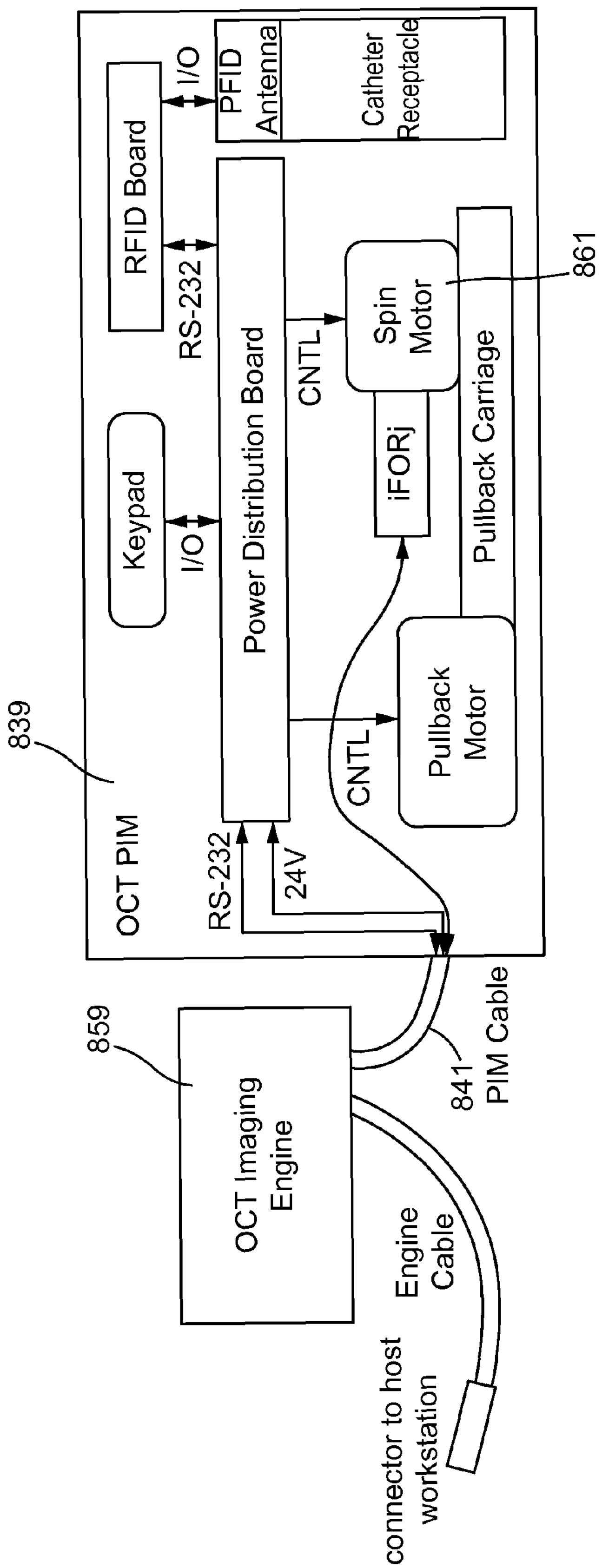
OCT PIM
839
RFID Board
PFID Antenna
Catheter Receptacle
I/O
RS-232
Keypad
I/O
Power Distribution Board
CNTL
Spin Motor
861
iFORj
Pullback Carriage
Pullback Motor
CNTL
RS-232
24V
OCT Imaging Engine
859
841
PIM Cable
Engine Cable
connector to host workstation

FIG.15

SYSTEMS AND METHODS FOR AMPLIFYING LIGHT

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of, and priority to, U.S. Provisional Patent Application No. 61/710,424, filed Oct. 5, 2012, the contents of which are incorporated by reference.

FIELD OF THE INVENTION

The invention generally relates to systems and methods for amplifying light.

BACKGROUND

Optical systems are used in a variety of applications that require amplified light at a particular wavelength, such as optical communication networks, medical imaging, and atmospheric remote sensing. Amplified light is provided by a light source that includes an optical amplifier. An optical amplifier amplifies light by passing it through a gain medium. The gain medium is a material that increases the power of light by stimulated emission when supplied with energy. Where laser light is desired, the gain medium is positioned between a pair of mirrors known as an optical cavity. Input light resonates between the mirrors while being re-amplified by the gain medium until the lasing threshold is surpassed and laser light is produced.

A gain medium has a peak gain associated with a transition frequency of its constituent elements. Light having a wavelength at the peak gain is more readily and more robustly amplified than light at other wavelengths. Consequently, the lasing threshold is lowest at the peak gain.

Where an optical system requires a particular wavelength of amplified light, the light source may include a tunable optical filter. Amplified light of a selected wavelength is obtained by tuning the filter to that wavelength and sending the light into the gain medium with sufficient input power to achieve a desired output power. However, while providing light of a selected wavelength, tunable optical filters also emit a low background level of light across a broad spectrum of wavelengths. When the input power is high enough to successfully amplify a selected frequency not at peak gain, the input power of background light at the peak gain can surpass the lasing threshold, resulting in undesired lasing, i.e., parasitic lasing. This so-called parasitic lasing leaches energy from the system, creates spurious spectral peaks, adds noise to optical signals, and diminishes the power of amplified light at the selected wavelength.

As a consequence, the useful range of a tunable filter is limited. For existing light sources to be used effectively, the tunable optical filter must be kept within a narrow tuning range surrounding the peak gain of the optical amplifier. Thus, once a light source is deployed in an optical system, use of the entire system is restricted by the gain medium of the optical amplifier to a narrow range of wavelengths defined by a peak gain of the gain medium. A variety of optical applications in medicine, research, and communication require a range of wavelengths of light broader than existing optical systems can handle and performing these applications requires multiple optical systems, each built around its own gain medium.

SUMMARY

The invention provides optical amplifier devices, systems, and methods that suppress parasitic lasing. Devices and

methods of the invention suppress parasitic lasing by employing wavelength-dependent reflectivity that inhibits reflection at a peak gain of a gain medium without inhibiting reflection at wavelengths not at the peak gain. Devices and methods of the invention inhibit reflection of light near the peak gain and even when a tunable filter is used, as low level background light from the filter does not exceed the lasing threshold of the gain medium. This allows the optical amplifier to amplify light across a broad range of wavelengths without parasitic lasing, thereby increasing the useable range of a tunable optical filter. In this manner, light at wavelengths not at a peak gain can be used effectively, and the gain medium of an optical amplifier does not limit use of a system to a narrow range of wavelengths associated with a peak gain of the gain medium. Thus, a single optical system according to the invention can be used for applications that require a broad range of wavelengths.

In certain aspects, the invention provides a method for amplifying light that includes transmitting light through a gain medium in which the light includes wavelengths at the peak gain of the gain medium and wavelengths not at the peak gain. Substantially all reflection of the light at the peak gain wavelengths is inhibited, thereby allowing amplification of the light not at the peak gain. The application provides techniques to selectively inhibit reflection at the peak gain wavelengths and not inhibit reflection at wavelengths not at the peak gain, preferably not inhibiting reflection at wavelengths both above and below the peak gain. In certain embodiments, the invention utilizes surface coatings that inhibit reflection in a wavelength-dependent matter, for example, inhibiting substantially all reflection at a peak gain. In certain embodiments, a gain medium is included that is solid with at least one surface facet that transmits or reflects light. Materials for use with systems and methods of the invention can be used to coat a facet of a gain medium or a surface in an optical path such as a mirror. A coated mirror can be any mirror within the optical path of a light source, such as one of the mirrors in a tunable etalon or either reflector in an optical cavity. In some embodiments, systems and methods of the invention use a wavelength-dependent mirror as an output coupler for a laser or optical amplifier.

By inhibiting substantially all reflection at the peak gain of a gain medium, the input power of an optical amplifier can be increased. Systems and methods of the invention diminish the power of those wavelengths of light corresponding to a lowest lasing threshold of the gain medium, allowing light of a selected wavelength to be usably amplified without parasitic lasing. By suppressing parasitic lasing in the gain medium, devices and methods of the invention allow a tunable optical filter to be tuned across a range of wavelengths greater than previously possible for a given gain medium. Methods of the invention can be used with any gain medium known in the art including, for example and without limitation, a semiconductor gain medium as found, for example, in a semiconductor optical amplifier or a booster optical amplifier.

In certain aspects, the invention provides a semiconductor optical amplifier including a semiconductor gain medium and a material that inhibits substantially all reflection at the peak gain, thus allowing the gain medium to amplify light at wavelengths not at the peak gain without parasitic lasing. The material can be provided as a mirror or as one of the facets of a solid gain medium. For example, an end facet of a semiconductor optical amplifier or booster optical amplifier or a mirror of an optical cavity can be coated with the material.

In other aspects, the invention provides a system for producing coherent light, including an optical amplifier with a reflector in optical communication with the optical amplifier in which the reflector inhibits reflection of light at the peak gain and reflects light at wavelengths not at the peak gain, thereby suppressing parasitic lasing. The optical amplifier produces coherent near infrared light from incident light delivered by a filter module in optical connection to the optical amplifier. Preferably, the reflector is an output coupler and the optical amplifier is a semiconductor optical amplifier. In certain embodiments, the system includes an output mechanism configured to be coupled to a fiber optic interferometer or other imaging device.

Systems and methods of the invention may be employed in any industry or application including, for example, medical imaging. In certain embodiments, the invention provides systems and methods for providing light for imaging tissue. For example, systems of the invention can generate coherent, near-infrared light without parasitic lasing for use in optical coherence tomography (OCT).

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates photon emission.

FIG. **2** is a schematic diagram of a semiconductor optical amplifier.

FIG. **3** shows the emission wavelengths of semiconductor materials.

FIG. **4** is a specification sheet for a booster optical amplifier.

FIG. **5** is a gain curve for a booster optical amplifier.

FIG. **6** shows an optical component.

FIG. **7** is a diagram of a laser.

FIG. **8** shows a gain curve showing a peak gain.

FIG. **9** shows wavelength dependent reflectivity of a material of the invention.

FIG. **10** is a diagram of a light path within an optical filter.

FIG. **11** is a diagram of an optical system according to certain embodiments of the invention.

FIG. **12** is a high-level diagram of a system for optical coherence tomography.

FIG. **13** is a schematic diagram of the imaging engine of an OCT system.

FIG. **14** is a diagram of a light path in an OCT system.

FIG. **15** shows the organization of a patient interface module in an OCT system.

DETAILED DESCRIPTION

The invention generally provides systems and methods for amplifying light using a gain component that includes a gain medium, in which the light includes wavelengths at a peak gain of the gain medium and wavelengths not at the peak gain. Any device that amplifies light that is compatible with systems and methods of the invention may be used as the gain component, such as, for example and without limitation, a semiconductor optical amplifier, a laser, or a booster optical amplifier. Systems and methods of the invention also include one or more components within an optical path that selectively inhibit reflection in a wavelength dependent fashion. Reflection can be inhibited by any method known in the art such as a coating on a surface. In certain embodiments, a mirror is provided having a surface coated to reflect light in a wavelength dependent manner.

Systems of the invention include gain components, components for wavelength dependent reflection, and any other compatible component known in the art including optical filters, fibers, coupling mechanisms, and interferometers. In certain embodiments, an optical filter is a tunable optical filter. Systems of the invention may further include other application-specific hardware, firmware, and software. For example, in certain embodiments, the invention generally relates to a system to operate as a light source for optical coherence tomography (OCT) for use in imaging a lumen biological tissue.

Systems of the invention generally include at least one gain component that amplifies the power of light that is transmitted through it. When light interacts with material, a few outcomes may be obtained. Light can be transmitted through the material unaffected or reflect off of a surface of the material. Alternatively, an incident photon of light can exchange energy with an electron of an atom within the material by either absorption or stimulated emission. As shown in FIG. **1**, if the photon is absorbed, the electron **101** transitions from an initial energy level E**1** to a higher energy level E**2** (in three-level systems, there is a transient energy state associated with a third energy level E**3**).

When electron **101** returns to ground state E**1**, a photon **105** is emitted. When photons are emitted, there is net increase in power of light within the gain medium. In stimulated emission, an electron emits energy ΔE through the creation of a photon of frequency v_{12} and coherent with the incident photon. Two photons are coherent if they have the same phase, frequency, polarization, and direction of travel. Equation 1 gives the relationship between energy change ΔE and frequency v_{12}:

$$\Delta E = h v_{12} \tag{1}$$

where h is Plank's constant. Light produced this way can be temporally coherent, i.e., having a single location that exhibits clean sinusoidal oscillations over time.

An electron can also release a photon by spontaneous emission. Amplified spontaneous emission (ASE) in a gain medium produces spatially coherent light, e.g., having a fixed phase relationship across the profile of a light beam.

Emission prevails over absorption when light is transmitted through a material having more excited electrons than ground state electrons—a state known as a population inversion. A population inversion can be obtained by pumping in energy (e.g., current or light) from outside. Where emission prevails, the material exhibits a gain G defined by Equation 2:

$$G = 10\ \mathrm{Log}_{10}(P_{out}/P_{in})\ \mathrm{dB} \tag{2}$$

where P_{out} and P_{in} are the optical output and input power of the gain medium.

Systems of the invention include one or more gain components for use as a light source. A gain component, generally, refers to any device known in the art capable of amplifying light such as an optical amplifier, laser, or any component employing a gain medium. A gain medium is a material that increases the power of light that is transmitted through the gain medium. Exemplary gain mediums include crystals (e.g., sapphire), doped crystals (e.g., yttrium aluminum garnet, yttrium orthovanadate), glasses such as silicate or phosphate glasses, gasses (e.g., mixtures of helium and neon, nitrogen, argon, or carbon monoxide), semiconductors (e.g., gallium arsenide, indium gallium arsenide), and liquids (e.g., rhodamine, fluorescein).

A gain component can be an optical amplifier or a laser. An optical amplifier is a device that amplifies an optical signal directly, without the need to first convert it to an electrical signal. An optical amplifier generally includes a gain medium (e.g., without an optical cavity), or one in which feedback from the cavity is suppressed. Exemplary optical amplifiers include doped fibers, bulk lasers, semiconductor optical amplifiers (SOAs), and Raman optical amplifiers. In doped fiber amplifiers and bulk lasers, stimulated emission in the amplifier's gain medium causes amplification of incoming light. In semiconductor optical amplifiers (SOAs), electron-hole recombination occurs. In Raman amplifiers, Raman scattering of incoming light with phonons (i.e., excited state quasiparticles) in the lattice of the gain medium produces photons coherent with the incoming photons.

Doped fiber amplifiers (DFAs) are optical amplifiers that use a doped optical fiber as a gain medium to amplify an optical signal. In a DFA, the signal to be amplified and a pump laser are multiplexed into the doped fiber, and the signal is amplified through interaction with the doping ions. The most common example is the Erbium Doped Fiber Amplifier (EDFA), including a silica fiber having a core doped with trivalent Erbium ions. An EDFA can be efficiently pumped with a laser, for example, at a wavelength of 980 nm or 1.480 nm, and exhibits gain, e.g., in the 1.550 nm region. An exemplary EDFA is the Cisco ONS 15501 EDFA from Cisco Systems, Inc. (San Jose, Calif.).

Semiconductor optical amplifiers (SOAs) are amplifiers that use a semiconductor to provide the gain medium. FIG. **2** is a schematic diagram of a semiconductor optical amplifier. Input light **213** is transmitted through gain medium **201** and amplified output light **205** is produced. An SOA includes n-cladding layer **217** and p-cladding layer **209**. An SOA typically includes a group III-V compound semiconductor such as GaAs/AlGaAs, InP/InGaAs, InP/InGaAsP and InP/InAlGaAs, though any suitable semiconductor material may be used. FIG. **3** shows the emission wavelengths of semiconductor materials.

A typical semiconductor optical amplifier includes a double heterostructure material with n-type and p-type high band gap semiconductors around a low band gap semiconductor. The high band gap layers are sometimes referred to as p-cladding and n-cladding layers (having, by definition, more holes than electrons and more electrons than holes, respectively). The carriers are injected into the gain medium where they recombine to produce photons by both spontaneous and stimulated emission. The cladding layers also function as waveguides to guide the propagation of the light signal. Semiconductor optical amplifiers are described in Dutta and Wang, Semiconductor Optical Amplifiers, 297 pages, World Scientific Publishing Co. Pte. Ltd., Hackensack, N.J. (2006), the contents of which are hereby incorporated by reference in their entirety.

Booster Optical Amplifiers (BOAs) are single-pass, traveling-wave amplifiers that only amplify one state of polarization generally used for applications where the input polarization of the light is known. Since a BOA is polarization sensitive, it can provide desirable gain, noise, bandwidth, and saturation power specifications. In some embodiments, a BOA includes a semiconductor gain medium (i.e., is a class of SOA). In certain embodiments, a BOA includes an InP/InGaAsP Multiple Quantum Well (MQW) layer structure. The input and output of BOA can be coupled to one or more waveguides on an optical amplifier chip. FIG. **4** is a specification sheet and FIG. **5** is a gain curve for a COTS booster optical amplifier.

As shown in FIG. **6**, optical amplifier components can be provided in a standard 14-pin butterfly package with either single mode fiber (SMF) or polarization maintain fiber (PMF) pigtails, which can be terminated with any fixed connection (FC) connector such as an angled physical connection (FC/APC) connector. Optional polarization-maintaining isolators can be provided at the input, output or both. In certain embodiments, the invention provides a wavelength dependent reflector as a reflective surface with an optical amplifier, such as a mirror or one of the facets of the gain medium.

A laser generally is an optical amplifier in which the gain medium is positioned within an optical resonator (i.e., an optical cavity) as diagramed in FIG. **7**. An optical resonator is an arrangement of mirrors that forms a standing wave cavity resonator for light waves, e.g., a pair of mirrors on opposite ends of the gain medium and facing each other. The pair includes high reflector **717** and output coupler **705** surrounding gain medium **701**. Incident light **721** reflects between the mirrors creating standing wave **713**. Some light is emitted as laser beam **709**. Where laser light is desired, the gain medium is positioned in an optical cavity. The optical cavity confines light in the gain medium, thereby feeding amplified light back through the amplification medium allowing it to be amplified again. Input light resonates between the mirrors while being re-amplified by the gain medium until the lasing threshold is surpassed and laser light is produced. This results in a positive feedback cycle tending to increase the gain G of the optical amplifier.

In a laser, one of the mirrors of the optical cavity is generally known as the high reflector while the other is the output coupler. Typically, the output coupler is partially transparent and emits the output laser beam. In certain embodiments, the invention provides a wavelength dependent reflector as a reflective surface with laser, such as one of the mirrors (e.g., the output coupler) or one of the facets of the gain medium.

A laser can be provided, for example, as a COTS component in a 14-pin butterfly package with either SMF or PMF pigtails. One such exemplary laser is the 980 nm pump laser module with Bragg grating sold under the mark POWERPURE 1998 PLM, available from Avanex Corporation (Fremont, Calif.).

In certain embodiments, a gain component such as an optical amplifier or a laser amplifies light in a frequency-specific manner. A gain component includes a gain medium having a gain coefficient g (gain per unit length) that is a function of the optical frequency of the incident signal w. The gain coefficient at a given frequency $g(\omega)$ is given by equation 3:

$$g(\omega)=g_0/(1+(\omega-\omega_0)^2T^2+P/Ps)$$

where g_0 is the peak gain of the medium, P is the optical power of the signal being amplified, Ps is the saturation power of the gain medium, ω_0 is an atomic transition frequency of the medium, and T is a dipole relaxation time. Where incident light has a frequency ω, a gain medium has a gain coefficient $g(\omega)$ and gain is given by Equation 4:

$$G(\omega)=\exp[g(\omega)L] \tag{4}$$

where L is a length of the gain medium.

The power of amplified light at a distance z from the input end of a gain medium is given by Equation 5:

$$P(z)=P_{in}\exp(gz) \tag{5}$$

Gain coefficient g has an inverse square relationship to $(\omega-\omega_0)$ (see Equation 3) and power P(z) is exponentially related to gain coefficient g. Thus, the gain of a gain medium is higher for optical frequencies ω closer to ω_0. FIG. **8** shows gain as a function of wavelength for a typical gain medium. As shown by the peak of the gain curve, the gain medium has a "peak gain".

If light of various wavelengths is amplified by the medium (at powers well below the saturation power Ps of the gain medium), light having a wavelength at or near the peak gain will be amplified to greater powers than light having a wavelength not at or near the peak gain.

For any wavelength of light, if the gain is greater than the loss, lasing can result in which the light is emitted as a laser beam. The conditions at which gain equals loss is the lasing threshold for a frequency of light. The lasing threshold is lowest at the peak gain and light having a wavelength at the peak gain is more readily and more robustly amplified than other wavelengths. Consequently, the gain medium most readily lases light at the peak gain.

Where this lasing is unintended, it is known as parasitic lasing. If light transmitted through the medium has sufficient power, wavelengths near the peak gain will cross the lasing threshold, causing lasing. This parasitic lasing leaches power from the system, reduces coherence length of signal light, and introduces noise into the signal. Due to the shape of the gain curve in a typical gain medium, parasitic lasing is problematic near the peak gain.

Devices and methods of the invention suppress parasitic lasing. In one embodiment, systems and methods of the invention suppress parasitic lasing by wavelength-dependent inhibition of reflection of light transmitted through a gain medium. By providing a system including a gain component and a wavelength dependent reflector, systems of the invention can provide amplified light of a selected wavelength without parasitic lasing at a peak gain.

Materials for use with systems and methods of the invention can be employed to selectively inhibit reflection at the peak gain and not inhibit reflection not at the peak gain. In certain embodiments inhibiting reflection is not at wavelengths both above and below the peak gain. Exemplary materials for use with systems and methods of the invention include surface coatings that inhibit reflection in a wavelength-dependent matter, for example, inhibiting substantially all reflection at a peak gain.

In general, a substrate with a reflective surface in which the surface is coated presents two reflective interfaces. The coated substrate provides an air/coating interface and a coating/substrate interface. A coating can be described in terms of physical thickness t and refractive index n, which together give an optical thickness nt of the coating.

If the reflections from each interface are out of phase by 180 degrees (π radians) then those reflections will interfere destructively, cancelling each other out (i.e., no light is reflected and all of the light will be transmitted through the material). To eliminate reflections at a specific wavelength λ, the optical thickness nt of the coating must be an odd number of quarter wavelengths λ of light as shown in Equation 6.

$$nt=N\,\lambda/4, \tag{6}$$

where N={1, 2, 3, . . . }. Generally, the refractive index n of the coating should be the square root of the refractive index of the substrate, as shown in Equation 7.

$$n_{coating}=\sqrt{n}_{substrate} \tag{7}$$

That is, where the substrate is glass, the coating should have a refractive index n of about 1.2 or so. Where multiple reflective coatings are used, cancellation is a product of the relative phase and intensity of the interfering beams. This cancellation can be controlled by controlling the relative optical thicknesses of the layers. For a given combination of coatings, there are typically two combinations of thicknesses that give zero reflectance at a given wavelength. Furthermore, two-layer antireflective coatings exhibit a curve of reflectance as a function of wavelength, generally having a V or U shape. This is shown in FIG. **9**.

Any material suitable for any antireflective coating may be used. Exemplary materials include metals such as aluminum, silver, or gold or compounds such as magnesium fluoride (MgF_2) in suitable thickness (e.g., single-layer quarter-wavelength coatings or multi-layered). Coated materials are sold under the trademark HEBBAR by CVI Melles Griot (Albuquerque, N. Mex.).

Coatings of the desired thickness can be fabricated by any method known in the art including, for example, vacuum deposition, electron bombardment vaporization, plasma ion-assisted deposition (PIAD), carbon vapor deposition, plasma vapor deposition, and related techniques. In vacuum deposition, a substrate is put in a vacuum chamber along with a metal crucible holding the coating substance. A high current (e.g., 100 A) is passed through the coating material, vaporizing it. Due to the vacuum, the vaporized material disperses to the material to be coated.

Materials for use with systems and methods of the invention can be used to coat a facet of a gain medium or a surface in an optical path such as a mirror. A coated mirror can be any mirror within the optical path of a light source, such as one of the mirrors in a tunable etalon or a reflector in a laser. In certain embodiments an output coupler of a semiconductor optical amplifier is coated with a wavelength dependent reflective material.

Where a mirror is coated with the wavelength dependent material, light at wavelengths not at the peak gain is reflected. In certain embodiments, the invention provides a substrate with a coated reflective surface (e.g., a coated mirror) that reflects light at wavelengths both above and below a peak gain. Inhibiting reflection in a wavelength dependent manner can be used to inhibit reflection at a peak gain of a gain medium of gain component thereby suppressing parasitic lasing. Thus, a light source according to the invention may be operated to produce amplified coherent light at wavelengths other than a peak gain of the gain medium without parasitic lasing near the peak gain.

Where an optical system requires a particular wavelength of amplified light, the light source may include an optical filter module such as a tunable optical filter in optical communication with a gain component. FIG. **10** is a diagram of a light path within an optical filter comprising a Fabry-Perot etalon. Etalons are discussed in Laufer, G., Introduction to Optics and Lasers in Engineering 1996, 476 pages, Cambridge University Press, Cambridge, UK, the contents of which are incorporated by reference herein in their entirety (see, e.g., §6.5 The Fabry-Perot Etalon, pp. 156-162). Optical filters are discussed in U.S. Pat. No. 7,035,484; U.S. Pat. No. 6,822,798; U.S. Pat. No. 6,459,844; U.S. Pub. 2004/0028333; and U.S. Pub. 2003/0194165, the contents of each of which are incorporated by reference herein in their entirety.

An optical filter typically has a peak reflectivity and a background reflectivity. The peak reflectivity indicates an amount of light output (reflected) at the specified wavelength, wherein a desired wavelength can be set (in a tunable filter) by placing mirrors in an etalon an appropriate distance apart. The background reflectivity indicates an amount of light output at wavelengths other than the desired wavelength.

Typical filters might have, for example, a 20% peak reflectivity and an 0.02% background reflectivity. The ratio of these number (10^3) defines the filter contrast ratio, expressed in decibels (dB) (here, 30 dB). Thus, if light of a certain wavelength, say 1200 nm, is intended, the filter will transmit light at 1200 nm as well as a broad spectrum of light at lower power in a ratio of 30 dB.

In some embodiments, systems of the invention include an optical filter that can be tuned to a desired wavelength, i.e., a tunable optical filter. Amplified light of a selected wavelength is obtained by tuning the filter to that wavelength and sending the light into the gain medium with sufficient input power to achieve a desired output power. An optical gain component (e.g., SOA, BOA, or laser) with a wavelength dependent material located in the light path suppress low-level background light across a broad spectrum of wavelengths. When the input power is high enough to successfully amplify a selected frequency not at peak gain, the input power of background light at the peak gain is suppressed, preventing parasitic lasing.

This allows the optical amplifier to amplify light across a broad range of wavelengths without parasitic lasing, thereby increasing the useable range of the tunable optical filter. In this manner, light at wavelengths not at a peak gain can be used effectively, and the gain medium of the optical amplifier does not limit use of a system to a narrow range of wavelengths associated with a peak gain of the gain medium. In this fashion, the tunable range of the tunable optical filter is increased.

In general, the invention provides systems for producing coherent light that include a gain component such as an optical amplifier with a reflector in optical communication with the optical amplifier, in which the reflector inhibits reflection of light at the peak gain and reflects light at wavelengths not at the peak gain, thereby suppressing parasitic lasing. FIG. **11** is a diagram of an optical system according to certain embodiments of the invention. Light **821** is transmitted through filter **825** and along light path **817**. Gain component **813** produces amplified coherent light **805** with a wavelength dependent material **801** in the light path. Amplified light **805** is sent to downstream component **809** as needed (e.g., an interferometer). The gain component produces coherent near infrared light from incident light delivered by a filter module in optical connection to the gain component. Preferably, the reflector is an output coupler and the gain component is a semiconductor optical amplifier. Systems of the invention further include any other compatible component known in the art. Exemplary components include interferometers, couplers/splitters, controllers, and any other device known in the art. Systems of the invention may include input and output mechanisms, such as an output mechanism configured to be coupled to a fiber optic interferometer or other imaging device. An optical system may include a controller component. For example, systems can include the LDC1300B butterfly LD/TEC controller from Thorlabs (Newton, N.J.). The LD/TEC controller and mount allows a system to be controlled by a computer. In certain embodiments, optical systems are integrated into an optical networking platform such as the Cisco ONS 15500 Dense Wave Division Multiplexer.

In certain embodiments, the system includes an interferometer such as a fiber optic interferometer. An interferometer, generally, is an instrument used to interfere waves and measure the interference. Interferometry includes extracting information from superimposed, interfering waves. Any interferometer known in the art can be used. In certain embodiments, an interferometer is included in a Mach-Zehnder layout, for example, using single mode optical fibers. A Mach-Zehnder interferometer is used to determine the relative phase shift between two collimated beams from a coherent light source and can be used to measure small phase shifts in one of the two beams caused by a small sample or the change in length of one of the paths.

Measuring a phase change in one of two beams from a coherent light is employed in optical coherence tomography (OCT). Commercially available optical coherence tomography systems are employed in diverse applications, including art conservation and diagnostic medicine, e.g., ophthalmology. Recently it has also begun to be used in interventional cardiology to help diagnose coronary artery disease. OCT systems and methods are described in U.S. Pub. 2011/0152771; U.S. Pub. 2010/0220334; U.S. Pub. 2009/0043191; U.S. Pub. 2008/0291463; and U.S. Pub. 2008/0180683, the contents of each of which are hereby incorporated by reference in their entirety.

Various lumen of biological structures may be imaged with aforementioned imaging technologies in addition to blood vessels, including, but not limited, to vasculature of the lymphatic and nervous systems, various structures of the gastrointestinal tract including lumen of the small intestine, large intestine, stomach, esophagus, colon, pancreatic duct, bile duct, hepatic duct, lumen of the reproductive tract including the vas deferens, vagina, uterus and fallopian tubes, structures of the urinary tract including urinary collecting ducts, renal tubules, ureter, and bladder, and structures of the head and neck and pulmonary system including sinuses, parotid, trachea, bronchi, and lungs.

In OCT, a light source delivers a beam of light to an imaging device to image target tissue. Within the light source is an optical amplifier and a tunable filter that allows a user to select a wavelength of light to be amplified. Wavelengths commonly used in medical applications include near-infrared light, for example, 800 nm for shallow, high-resolution scans or 1700 nm for deep scans.

Generally, there are two types of OCT systems, common beam path systems and differential beam path systems, that differ from each other based upon the optical layout of the systems. A common beam path system sends all produced light through a single optical fiber to generate a reference signal and a sample signal whereas a differential beam path system splits the produced light such that a portion of the light is directed to the sample and the other portion is directed to a reference surface. The reflected light from the sample is recombined with the signal from the reference surface for detection. Common beam path interferometers are further described for example in U.S. Pat. No. 7,999,938; U.S. Pat. No. 7,995,210; and U.S. Pat. No. 7,787,127, the contents of each of which are incorporated by reference herein in its entirety.

In a differential beam path system, amplified light from a light source is input into an interferometer with a portion of light directed to a sample and the other portion directed to a reference surface. A distal end of an optical fiber is interfaced with a catheter for interrogation of the target tissue during a catheterization procedure. The reflected light from the tissue is recombined with the signal from the reference surface forming interference fringes (measured by a photovoltaic detector) allowing precise depth-resolved imaging of the target tissue on a micron scale. Exemplary differential beam path interferometers are Mach-Zehnder interferometers and Michelson interferometers. Differential beam path interferometers are further described for example in U.S. Pat. No. 7,783,337; U.S. Pat. No. 6,134,003; and U.S. Pat. No. 6,421,164, the contents of each of which are incorporated by reference herein in its entirety.

In certain embodiments, the invention provides a differential beam path OCT system with intravascular imaging capability as illustrated in FIG. **12**. For intravascular imaging, a light beam is delivered to the vessel lumen via a fiber-optic based imaging catheter **826**. The imaging catheter is connected through hardware to software on a host workstation. The hardware includes an imagining engine **859** and a handheld patient interface module (PIM) **839** that includes user controls. The proximal end of the imaging catheter is connected to PIM **839**, which is connected to an imaging engine as shown in FIG. **12**.

As shown in FIG. **13**, the imaging engine **859** (e.g., a bedside unit) houses a power supply **849**, light source **827**, interferometer **931**, and variable delay line **835** as well as a data acquisition (DAQ) board **855** and optical controller board (OCB) **854**. A PIM cable **841** connects the imagine engine **859** to the PIM **839** and an engine cable **845** connects the imaging engine **859** to the host workstation.

FIG. **14** shows light path in an exemplary embodiment of the invention. Light for image capture originates within the light source **827**. This light is split between an OCT interferometer **905** and an auxiliary interferometer **911**. The OCT interferometer generates the OCT image signal and the auxiliary, or "clock", interferometer characterizes the wavelength tuning nonlinearity in the light source and generates a digitizer sample clock.

In certain embodiments, each interferometer is configured in a Mach-Zehnder layout and uses single mode optical fibers to guide the light. Fibers are connected via either LC/APC connectors or protected fusion splices. By controlling the split ratio between the OCT and auxiliary interferometers with splitter **901**, the optical power in the auxiliary interferometer is controlled to optimize the signal in the auxiliary interferometer. Within the auxiliary interferometer, light is split and recombined by a pair of 50/50 coupler/splitters.

Light directed to the main OCT interferometer is also split by splitter **917** and recombined by splitter **919** with an asymmetric split ratio. The majority of the light is guided into the sample path **913** and the remainder into a reference path **915**. The sample path includes optical fibers running through the PIM **839** and the imaging catheter **826** and terminating at the distal end of the imaging catheter where the image is captured.

Typical intravascular OCT involves introducing the imaging catheter into a patient's target vessel using standard interventional techniques and tools such as a guidewire, guide catheter, and angiography system. When operation is triggered from the PIM or control console, the imaging core of the catheter rotates while collecting image data that it delivers to the console screen. Rotation is driven by spin motor **861** while translation is driven by pullback motor **865**, shown in FIG. **15** Blood in the vessel is temporarily flushed with a clear solution while a motor translates the catheter longitudinally through the vessel.

In certain embodiments, the imaging catheter has a crossing profile of 2.4 F (0.8 mm) and transmits focused OCT imaging light to and from the vessel of interest. Embedded microprocessors running firmware in both the PIM and imaging engine control the system. The imaging catheter includes a rotating and longitudinally-translating inner core contained within an outer sheath. Using light provided by the imaging engine, the inner core detects reflected light. The reflected, detected light is transmitted along the sample path to be recombined with the light from the reference path.

A variable delay line (VDL) **925** on the reference path uses an adjustable fiber coil to match the length of the reference path **915** to the length of the sample path **913**. The reference path length is adjusted by translating a mirror on a lead-screw-based translation stage that is actuated electromechanically by a small stepper motor. The free-space optical beam on the inside of the VDL **925** experiences more delay as the mirror moves away from the fixed input/output fiber. Stepper movement is under firmware/software control.

Light from the reference path is combined with light from the sample path. This light is split into orthogonal polarization states, resulting in RF-band polarization-diverse temporal interference fringe signals. The interference fringe signals are converted to photocurrents using PIN photodiodes **929***a*, **929***b*, . . . on the OCB **851** as shown in FIG. **14**. The interfering, polarization splitting, and detection steps are done by a polarization diversity module (PDM) on the OCB. Signal from the OCB is sent to the DAQ **855**, shown in FIG. **13**. The DAQ includes a digital signal processing (DSP) microprocessor and a field programmable gate array (FPGA) to digitize signals and communicate with the host workstation and the PIM. The FPGA converts raw optical interference signals into meaningful OCT images. The DAQ also compresses data as necessary to reduce image transfer bandwidth to 1 Gbps (e.g., lossily compressing frames using a JPEG encoder).

In certain embodiments, the invention provides a light source for OCT including an optical filter, a gain component, and a wavelength dependent material to selectively inhibit reflection at a peak gain of a gain medium of the optical amplifier.

Any filter known in the art compatible with the invention may be used including, for example, a tunable optical filter. The filter is included to deliver light of a specified wavelength into the optical amplifier. The filter typically has a peak reflectivity and a background reflectivity. In some embodiments, a system includes a commercial, off-the-shelf (COTS) filter. One exemplary filter for use with the invention is filter module TFM-687 by Axsun Technologies, Inc. (Billerica, Mass.). An exemplary tunable optical filter exhibits 20% reflectivity and a 29 dB contrast ratio. Although a tunable optical filter from Asxun Technologies has been described as a possible tunable optical filter to be used with the invention, any tunable optical filter, such as is well understood in the art, may be used in the present invention.

Any optical amplifier or laser known in the art and compatible with the invention may be used as the gain component including, for example, a semiconductor optical amplifier. The amplifier amplifies the light to a sufficient output power for imagining by OCT. The amplifier typically has a semiconductor gain medium and an optical cavity. In some embodiments, a system includes a COTS amplifier. One exemplary optical amplifier for use with the invention is booster optical amplifier serial number BOA1130S, BOA1130P, or BOA-8702-11820.4.B01 from Thorlabs (Newton, N.J.). An exemplary optical amplifier has a center wavelength of 1285 nm and a small signal gain of 30 dB with a chip length of 1.5 mm (See specifications in FIG. **4**)

A mirror can be coated with wavelength dependent material, for example and as well known in the art, as shown in FIG. **9**. Material coatings are available from Unioriental Optics Co., Ltd. (Zhong Guan Cun Science Park, Beijing, China).

In certain embodiments, the invention provides systems and methods for amplifying light for OCT such as diagrammed in FIG. **13**. Exemplary components of light source **827** are illustrated in FIG. **11**. Tunable optical filter **825** provides light to gain component **813** and the system further includes wavelength dependent mirror **801**. Gain component **813** including a gain medium is provided by a BOA having specification as shown in FIGS. **4**-**5** (e.g., generally having a form factor as illustrated in FIG. **6**). Filter **825** set at near infrared wavelengths produces light having wavelengths at a peak gain of the gain medium (e.g., about 1300 nm) and wavelengths not at a peak gain (e.g., about 1200 nm). This light is transmitted through the gain medium. Wavelength dependent mirror **801** exhibits reflectivity in a wavelength dependent manner as shown by the curve in FIG. **9** and thus inhibits substantially all reflection at wavelengths at the peak gain, thereby allowing amplification of light at wavelengths not at the peak gain. Light source **827** thus provides light at wavelengths below the peak gain (e.g., at about 1200 nm) to interferometer **831** without parasitic lasing and can similarly provide light at wavelengths above the peak gain. Tunable optical filter **825** in light source **827** included within imaging engine **927** (FIG. **13**) can be tuned to wavelengths below and above the peak gain to a greater degree than without wavelength dependent reflector **801**, and the system operates without parasitic lasing to produce coherent near infrared light.

INCORPORATION BY REFERENCE

References and citations to other documents, such as patents, patent applications, patent publications, journals, books, papers, web contents, have been made throughout this disclosure. All such documents are hereby incorporated herein by reference in their entirety for all purposes.

EQUIVALENTS

Various modifications of the invention and many further embodiments thereof, in addition to those shown and described herein, will become apparent to those skilled in the art from the full contents of this document, including references to the scientific and patent literature cited herein. The subject matter herein contains important information, exemplification and guidance that can be adapted to the practice of this invention in its various embodiments and equivalents thereof.

What is claimed is:

1. An optical coherence tomography (OCT) system with intravascular imaging capability, said OCT system comprising:
- a fiber-optic based imaging catheter; and
- an imaging engine connected to the fiber-optic based imaging catheter, said imaging engine comprising a light source and said light source comprising:
  - a gain medium having a peak gain at a near infrared wavelength; and
  - a mirror comprising a wavelength dependent material having a minimum reflectivity at the near infrared wavelength, thereby allowing the gain medium to amplify light at wavelengths not at the peak gain.

2. The OCT system of claim **1**, wherein the mirror reflects light at a desired wavelength.

3. The OCT system of claim **1**, wherein the wavelength dependent material does not inhibit reflection at wavelengths above and below the peak gain.

4. The OCT system of claim **1**, wherein the wavelength dependent material constitutes an output coupler.

5. The OCT system of claim **1**, further comprising an output coupler.

6. An optical coherence tomography (OCT) system with intravascular imaging capability, said OCT system comprising:
- a fiber-optic based imaging catheter; and
- an imaging engine connected to the fiber-optic based imaging catheter, said imaging engine comprising a light source and said light source comprising:
- an optical amplifier comprising a gain medium having a peak gain at a near infrared wavelength; and
- a reflector in optical communication with the optical amplifier and comprising a wavelength dependent material having a minimum reflectivity at the near infrared wavelength, wherein the reflector inhibits reflection of light at wavelengths at the peak gain and reflects light at wavelengths not at the peak gain, thereby suppressing parasitic lasing.

7. The OCT system of claim **6**, wherein the optical amplifier produces coherent near-infrared light.

8. The OCT system of claim **6**, further comprising a filter module in optical connection to the optical amplifier.

9. The OCT system of claim **6**, wherein the reflector is an output coupler.

10. The OCT system of claim **6**, wherein the optical amplifier is a semiconductor optical amplifier.

11. The OCT system of claim **6** further comprising an output mechanism configured to be coupled to a fiber optic interferometer.

12. A method for intravascular imaging, comprising the steps of:
- transmitting light comprising peak gain and non-peak gain wavelengths through a gain medium, wherein the peak gain is at a near infrared wavelength;
- inhibiting substantially all reflection at peak gain wavelengths, thereby allowing amplification of light at non-peak gain wavelengths directing the amplified light to an optical coherence tomography (OCT) system with intravascular imaging capability, said OCT system comprising:
  - a fiber-optic based imaging catheter;
  - a patient interface module (PIM); and
  - an imaging engine;
  - wherein the fiber-optic based imaging catheter is optically coupled to the PIM and the PIM is optically coupled to the imaging engine.

13. The method of claim **12**, wherein reflection is not inhibited at wavelengths both above and below the wavelengths at the peak gain.

14. The method of claim **12**, wherein the gain medium comprises a semiconductor.

15. The method of claim **14**, further comprising lasing the light at one of the non-peak gain wavelengths.

16. The method of claim **14** wherein the amplified light is coherent near-infrared light.

17. The method of claim **12**, wherein the inhibiting step comprises providing a mirror to reflect the light at non-peak gain wavelengths and inhibit reflection of light at the wavelengths at the peak gain.

18. The method of claim **17**, wherein the mirror is an output coupler.

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